

A comparison of the physiological consequences of head-loading and back-loading for African and European women

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Abstract: Aim: to quantify the physiological cost of head-load carriage and to examine the 'free ride' hypothesis for head-load carriage in groups of women differing in their experience of headloading. Method: Twenty four Xhosa women (13 experienced head-loaders (EXP), 11 with no experience of head-loading (NON)) attempted to carry loads of up to 70% of body mass (BM) on both their heads and backs whilst walking on a treadmill at a self selected walking speed. Expired air was collected throughout. In a second study nine women, members of the British Territorial Army (TA), carried similar loads, again at a self selected speed. Results: Maximum load carried was greater for the back than the head ($54.7 \pm 15.1\%$ v $40.8 \pm 13.2\%$ BM, $P < 0.0005$). Considering study one, head-loading required a greater oxygen rate than back-loading (10.1 ± 2.6 ml.kgbodymass⁻¹.min⁻¹ v 8.8 ± 2.3 ml.kgbodymass⁻¹.min⁻¹, $P = 0.043$, for loads 10-25%BM) regardless of previous head-loading experience ($P = 0.333$). Percentage changes in oxygen consumption associated with head-loading were greater than the proportional load added in both studies but were smaller than the added load for the lighter loads carried on the back in study 1. All other physiological variables were consistent with changes in oxygen consumption. Conclusion: The data provides no support for the 'free ride' hypothesis for head-loading although there is some evidence of energy saving mechanisms for back-loading at low speed/load combinations. Investigating the large individual variation in response may help in identifying combinations of factors that contribute to improved economy.

1. Introduction

The necessity to transport relatively heavy loads remains an important occupational task for many people, including school students and the military. Consequently much attention has been paid to load carriage with a number of different approaches evident in the literature. The analytical perspectives employed include: kinematics (e.g. Sharpe *et al*, 2008; LaFiandra *et al*, 2003), kinetics (e.g. Chow *et al*, 2005; Birrell *et al*, 2007), electromyography (e.g. Al-Khabbaz *et al*, 2008; Bobet and Norman, 1984) and subjective perceptual responses (e.g. Birrell and Hooper, 2007; Mackie and Legg, 2008). By far the most prevalent approach, however, has been an examination of the physiological consequences of carrying loads (e.g. Bastien *et al*, 2005a; Abe *et al*, 2004). For the most part these analyses have considered the energetic consequences of load carriage through an examination of oxygen consumption.

One particular area that has been explored in some detail is that of the effect of load placement and load carrying method on energy expenditure. Taylor *et al* (1980) demonstrated, across a range of species, that, for loads carried on the back, the increase in energy expenditure associated with a given load was directly proportional to the relative increase in mass i.e. an additional load of 10% body mass evokes a 10% increase in energy expenditure. This result has been replicated in numerous human studies (e.g. Quesda *et al*, 2000; Rorke, 1990). Studies examining the effect of load placement on energy expenditure have generally shown significant advantages for load placements close to the trunk as opposed to loads carried more distally, in the hands or on the feet (e.g. Soule and Goldman

1969). There are, however, either only small or no advantages for particular loading methods when the methods compared all involve loading of the trunk (e.g. Kirk and Schneider, 1992; Holewijn, 1990). Datta and Ramanathan (1971) and Legg and Mahanty (1985) both compared a range of loading conditions and found small advantages for double pack systems, where the load was carried split between the back and the front of the trunk, over back-loading alone. These findings were supported by Lloyd and Cooke (2000a). Stuempfle *et al* (2004) reported a significant advantage for loads carried high on the back compared to loads carried in a low position. Similarly, Obusek *et al* (1997) examined the effect of the location of the centre of mass of a backpack on energy cost. They found a significant linear relationship between the position of the centre of mass and energy cost with positions close to the body and high on the back being associated with lower metabolic cost.

In the developing world heavy loads are regularly carried over long distances as a necessary part of daily routine. Most commonly the method employed is some form of head-loading, either with the load carried on the back but supported by a forehead strap (e.g. Nepalese porters) or directly on the head (e.g. African women). It has been argued that both of these methods represent particularly economical solutions to the problem of carrying loads in these environments (Maloiy *et al*, 1986; Charteris *et al* (1989 a,b); Bastien *et al*, 2005b). The head strap method has received some recent attention. Minetti *et al* (2006) concluded that the remarkable capabilities of the Himalayan porters could only partially be explained by metabolic efficiency whilst Malville *et al* (2001) argued that a combination of pacing strategy and metabolic efficiency contribute to the load carrying abilities of the commercial porters in Eastern Nepal. Both studies seem

to support the early findings of Nag *et al* (1979) who reported this method as being particularly economical when heavy loads are carried at relatively slow speeds.

The data for direct head-loading are more inconsistent. Maloiy *et al* (1986) reported a phenomenon whereby African women could carry loads of up to 20% body mass with no additional energy expenditure, with a linear relationship thereafter (i.e. loads of 30% body mass required a 10% increase in energy expenditure). This ability to carry loads of up to 20% body mass with no additional energy expenditure above that required for unloaded walking has become known as the ‘free ride’ hypothesis (Charteris *et al*, 1989). The findings of Maloiy *et al* (1986) were particularly interesting as they suggested that both direct head-loading and the forehead strap method were exceptionally economical regardless of the method employed. The study involved a total of five women from two different ethnic groups, each of which employed a different head-loading method. The Luo women (n=3) carried the loads directly on their heads whilst the Kikuyu women (n=2) carry the loads on their backs, supported by a head strap. Charteris *et al* (1989) provide support for the ‘free ride hypothesis’ based on a study involving six Xhosa women who were direct head-loaders. Jones *et al* (1987) suggested that the existence of a ‘free ride’ was predicated on the relative contribution of body fat to the overall load. Of the eight Mandinka women they assessed, all employing the direct head-loading method, four appeared to follow the patterns indicated by Maloiy *et al* (1986) whilst the remainder demonstrated the more typical proportional response. The defining characteristic of the two groups was body composition and Jones *et al* (1987) concluded that African women could be extremely economical load carriers only

if they were lean. They suggested that any external load and body fat combination up to 140% fat free mass could be carried, directly on the head, with no additional energy expenditure.

In contrast to Maloiy *et al* (1986), Jones *et al* (1987) and Charteris *et al* (1989), the earlier studies of Soule and Goldman (1969), Datta and Ramanathan (1971) and Datta *et al* (1973) all suggest that the energy cost of direct head-loading is broadly in line with the proportional increase associated with back-loading. Thus, it is striking that there has been no systematic investigation into the generalisability of the free-ride hypothesis. Rather the subsequent literature has sought to biomechanically explain the phenomenon and has been based around reinterpretation and analysis of the physiological data from Maloiy (1986) (e.g. Heglund *et al*, 1995). No contemporary physiological data exists for head-loading in African women. The purpose of this study was, therefore, to provide a more comprehensive description of the physiological consequences of head-loading for both experienced and not experienced participants than currently exists in the literature and, via comparison with back-loading, provide a more systematic investigation of the ‘free ride’ hypothesis.

2. Methods

2.1 Participants

Twenty four Xhosa women, thirteen with at least ten years experience of head load carriage (EXP) and eleven with no experience of head load carriage (NON)

were recruited to take part in study 1, whilst nine British women, all members of the Territorial Army with no experience of head load carriage but significant experience of back-loading, took part in study 2 (TA). All participants gave informed consent for their participation in the studies. Both studies had received ethical approval through standard institutional review procedures at both the University of Abertay Dundee and Cape Peninsula University of Technology.

The women in all three groups were of similar age (22.5 ± 2.1 , 21.2 ± 2.4 and 21.8 ± 1.8 years for EXP, NON and TA respectively, $P=0.765$) and body mass (66.0 ± 12.8 , 66.8 ± 14.5 and 67.4 ± 8.4 kg for EXP, NON and TA respectively, $P=0.967$). The TA group were, however, significantly taller than either the EXP or NON groups (165 ± 5.4 cm v 159 ± 5.1 cm and 158 ± 5.3 cm respectively, $P=0.011$)

2.2 Study 1

2.2.1 Experimental Procedures

The women each attended the Human Performance Laboratory at Cape Peninsula University of Technology on three separate occasions. On the first occasion participants were screened for any potential contraindications to exercise, stature and mass were assessed, and questionnaires were completed relating to load carriage history. The women were then habituated to the experimental protocol and the equipment to be used. A typical habituation session lasted between twenty and thirty minutes and involved the women walking on the treadmill at

various speeds both with and without a face mask. In addition they also tried out the two load carrying devices, a standard 45l backpack (Karrimor, SA) for back loading and a plastic crate for head loading (the crate placed either directly on the head or on a small piece of rolled cloth to provide some cushioning), with and without loads. At the end of the session the women were asked to walk on the treadmill at a speed that they felt would be comfortable when carrying a heavy load. The chosen walking speed of each participant was noted and used for the subsequent experimental trials.

On arrival at the laboratory at the next visit each participant chose at random, via the picking of a piece of paper (marked with either 'H' or 'B') from a hat, the loading method for the first experimental trial. This involved walking, at the previously determined speed, for four minutes unloaded and then, after a one minute rest, a load of 10% body mass was added. This load was then carried for a further four minutes. After a further rest of one minute the load was increased to 15% and carried for four minutes. This pattern was repeated with loads of 20%, 25%, 30%, 40%, 50%, 60% and 70% of body mass or until pain and discomfort led to voluntary cessation of the session. Workloads of four minutes duration were employed based on pilot work which showed that steady state oxygen consumption was achieved within this time. This is consistent with previous studies in the area (e.g. Lloyd *et al* 2000a) The load was calculated based on the body mass at the habituation session and was made up of the mass of the actual carrying device plus appropriate weightlifting plates, (between 2.5 kg and 10 kg), and 100g sandbags, which allowed the load to be adjusted to within 50g of the required load. Each participant attended the laboratory one week later to repeat the experiment with the other loading device.

2.2.2 Data collection and analysis

All participants were fitted with a face mask and expired air was collected throughout the protocol by means of an on-line gas analysis system (Quark b2, Cosmed, Rome). The system was calibrated prior to each test in accordance with manufacturer's instructions using gases of known concentration (16% O₂, 4% CO₂) and room air. Participants were also fitted with a heart rate monitor (Polar, Finland). All measured cardiorespiratory variables (oxygen consumption, minute ventilation, carbon dioxide production, breathing frequency, tidal volume and heart rate) were subsequently averaged over the final minute of each workload. These were then analysed using an ANOVA with repeated measures (SPSS, v16.0). All multiple comparisons were accomplished after use of a Bonferroni correction. Percentage changes over unloaded walking were calculated for key variables and compared via a repeated measures group x method ANOVA. In study 1 all women carried at least 25% BM in both conditions whilst in study 2 all women carried at least 30% BM in both conditions. The analysis will reflect this with, for study 1 data, method x group x load ANOVAs for 0-25% BM and method x load ANOVAs for loads of 0 -30% BM for study 2. For study 1 a further method x group ANOVA will be used to analyse data at 30% BM (n=10 for both NON and EXP) and a simple ANOVA comparing method will be performed to analyse data at 40% BM (n=12, 8 EXP, 4 NON) and 50% BM (n=7, 5 EXP, 2 NON.)

Maximum load carried was recorded and compared between the groups and

conditions by means of a further ANOVA with repeated measures. Univariate ANOVA was used to assess differences in physical characteristics and walking speed between the three groups.

2.3 Study 2

The second study took place at the Human Performance Laboratory of the University of Abertay Dundee and differed from study 1 only in respect of: the loads to be carried (0, 10%, 20%, 30%, 40%, 50% 60% and 70% BM), the online gas analysis system which was a Metalyzer 3b (Cortex, Germany), the backpack used was a standard British Army issue Bergen and the walking speed was $4.33 \pm 0.19 \text{ km}\cdot\text{h}^{-1}$, significantly faster than either the EXP or the NON groups in study 1 ($P < 0.0005$).

3. Results

3.1 Chosen walking speed

The walking speeds chosen by the women in study 1 were not significantly different (3.15 ± 0.45 and $3.00 \pm 0.30 \text{ km}\cdot\text{h}^{-1}$ for EXP and NON respectively, $P = 0.607$). These speeds were, however, significantly slower than the walking speed chosen by the TA women ($4.33 \pm 0.19 \text{ km}\cdot\text{h}^{-1}$, $P < 0.0005$)

3.2 Load carried

Considering study 1, significantly greater load was carried on the back than on the head ($P=0.014$), with the average maximum load associated with head-carriage being $41.5 \pm 14.4\%$ BM versus $51.5 \pm 15.8\%$ BM for back load carriage. These equate to absolute loads of 26.8 ± 8.6 kg and 33.2 ± 9.4 kg respectively. There was no significant difference between the groups overall ($P=0.308$) and the response was consistent between the two groups ($P=0.845$) with mean differences were 5.9 kg and 6.8 kg for the EXP and NON groups respectively. Two of the EXP group and four of the NON group carried more on their head than on their back, five EXP carried the same in both conditions whilst six EXP and seven NON carried more on their backs than on their heads. Considering the TA group the load carried on the back, $63.3 \pm 8.7\%$ BM, was significantly greater than the load carried on the head ($P=.001$), $38.9 \pm 9.3\%$ BM. These equate to absolute loads of 43.1 ± 10.0 kg and 25.9 ± 5.3 kg respectively. One of the TA group carried the same load in both conditions whilst the rest carried more on their backs.

3.3 Oxygen Consumption

Considering study 1, unloaded oxygen consumption ($\text{ml.kg}^{-1}.\text{min}^{-1}$) was not different between the successive measurements in each of the two conditions ($8.3 \pm 2.1 \text{ ml.kg}^{-1}.\text{min}^{-1}$ v $7.7 \pm 1.8 \text{ ml.kg}^{-1}.\text{min}^{-1}$ for head- and back-loading respectively, $P= 0.261$). Considering all loads 10-25% BM oxygen consumption was greater than the unloaded condition ($P<0.0005$) and, moreover, the average oxygen consumption across all loads associated with head-loading was significantly greater than that associated with back-loading ($10.1 \pm 2.6 \text{ ml.kg}^{-1}.\text{min}^{-1}$ v $8.8 \pm 2.3 \text{ ml.kg}^{-1}.\text{min}^{-1}$ respectively, $P=0.043$). The pattern of response between the groups was consistent (method x group interaction, $P=0.333$, figure 1

and table 1) as was the pattern across increasing loads (method x load interaction $P=0.120$). There was also a significantly greater oxygen consumption associated with the head loading condition at the 30% BM load ($11.4 \pm 3.3 \text{ ml.kg}^{-1}.\text{min}^{-1}$ v $9.6 \pm 2.9 \text{ ml.kg}^{-1}.\text{min}^{-1}$ for head- and back-loading respectively, $P=0.041$, $n=15$) but not at either 40% BM ($11.6 \pm 3.1 \text{ ml.kg}^{-1}.\text{min}^{-1}$ v $10.4 \pm 3.6 \text{ ml.kg}^{-1}.\text{min}^{-1}$, $P=0.249$, $n=11$) or 50% BM ($12.2 \pm 2.9 \text{ ml.kg}^{-1}.\text{min}^{-1}$ v $11.3 \pm 4.2 \text{ ml.kg}^{-1}.\text{min}^{-1}$, $P=0.247$, $n=7$). Again the pattern of response was consistent across the groups with group by method interactions of $P=0.780$ at 30% BM and $P=0.280$ at 40% BM.

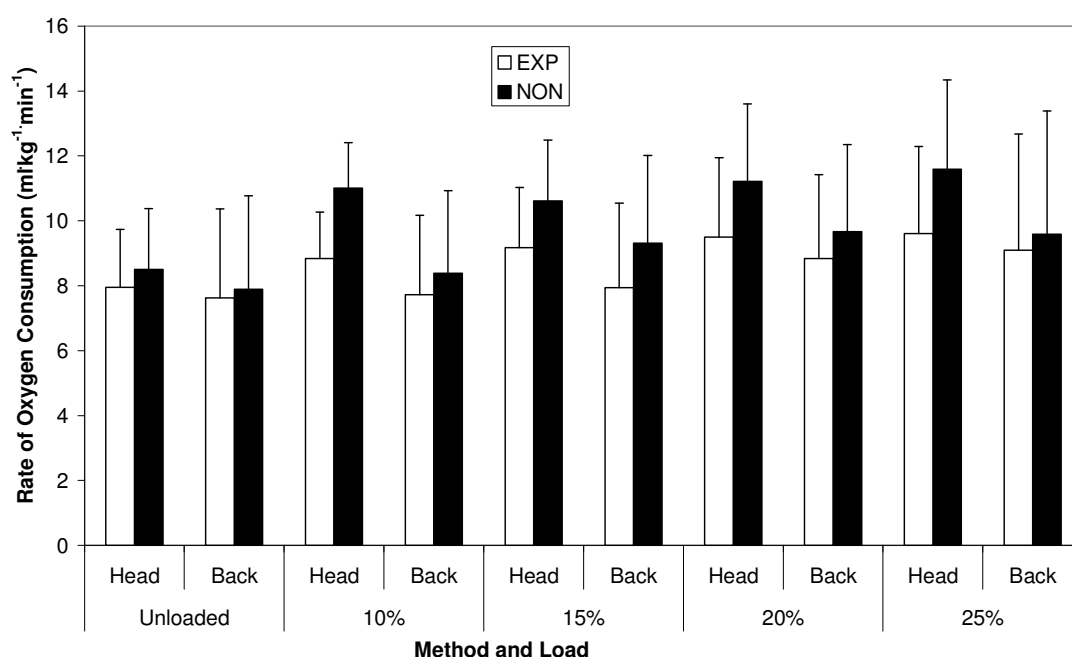


Fig 1 Mean (+s) Oxygen Consumption ($\text{ml.kg}^{-1}.\text{min}^{-1}$) for each group at loads of 10-25% BM in each condition for study 1

Considering study 2, unloaded oxygen consumption ($\text{ml.kg}^{-1}.\text{min}^{-1}$) was not different between the two successive measurements in each of the two conditions ($11.6 \pm 1.4 \text{ ml.kg}^{-1}.\text{min}^{-1}$ v $11.3 \pm 1.3 \text{ ml.kg}^{-1}.\text{min}^{-1}$ for head- and back-loading

respectively, $P=0.598$). Oxygen consumptions associated with all loads were greater than the unloaded condition ($P<0.0005$). Considering all loads 10-30% BM, there was no difference in oxygen consumption associated with the head and back conditions ($15.2 \pm 2.6 \text{ ml.kg}^{-1}.\text{min}^{-1}$ v $14.2 \pm 2.1 \text{ ml.kg}^{-1}.\text{min}^{-1}$ respectively, $P=0.081$). Responses were consistent with increasing load ($P=0.706$ for the method x load interaction, figure 2 and table 1).

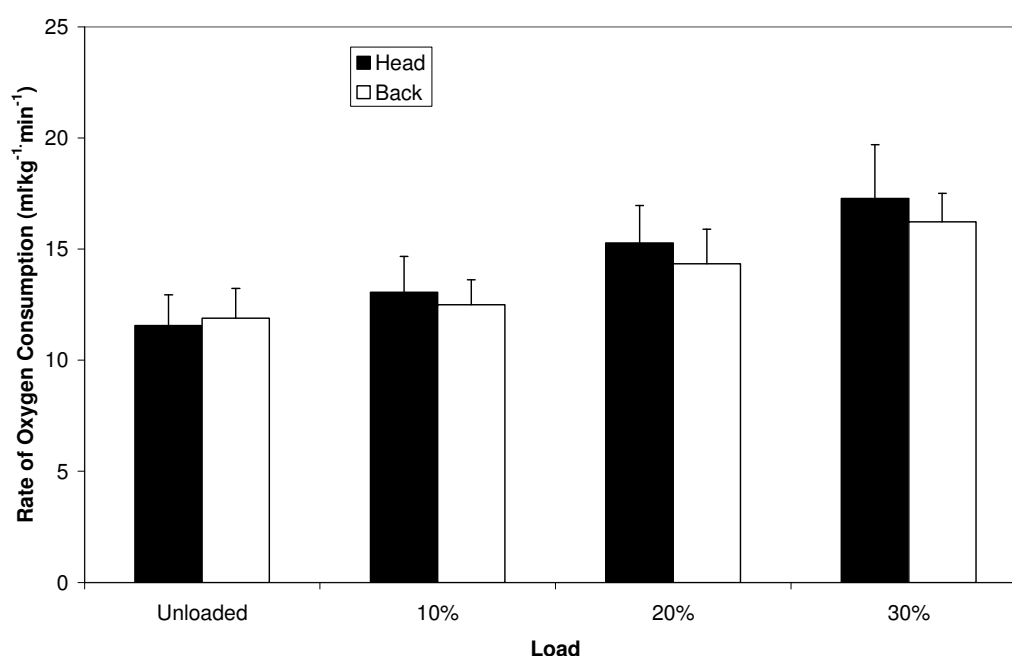


Fig 2 Mean (+s) Oxygen Consumption ($\text{ml.kg}^{-1}.\text{min}^{-1}$) at loads of 10-30% BM in each condition for study 2

Figure 3 shows the percentage difference in oxygen consumption above the unloaded condition in each condition for both studies. In the case of study 1, and in the light of the lack of group interaction effects data is calculated for EXP and NON combined. The line $y=x$ is added to aid comparison between each condition and a directly proportionate response.

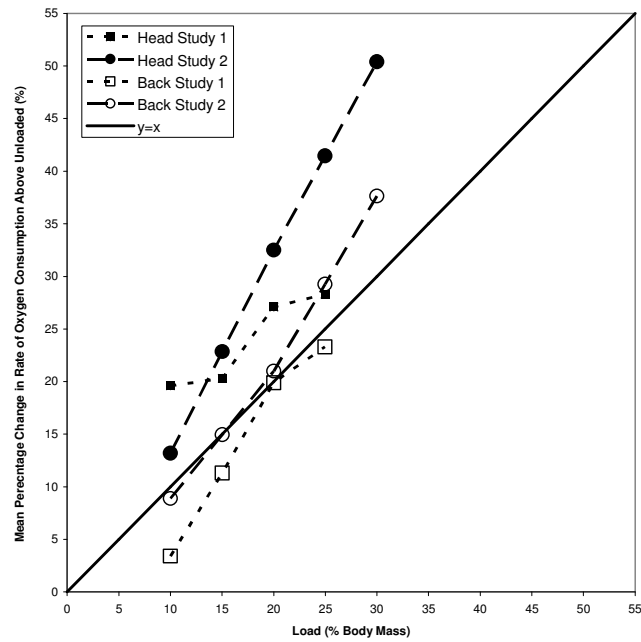


Fig 3 Mean percentage difference in oxygen consumption in each of the loading conditions for all participants in both study 1 and study 2

3.4 Other Cardiorespiratory variables

The lack of interaction effects involving group for study 1 (EXP and NON) was consistent across the rest of the variables measured. Consequently Table 1 contains combined data for both groups in study 1. The data in table 1 suggest that the pattern of response for all other variables measured is similar to that for the oxygen consumption data. This is summarized in figure 4 which shows a summary of percentage differences, calculated as increase above back-load condition for head-loading, presenting mean values across 10-25% BM loads for study 1 and 10-30% BM loads for study 2, for each variable.

Table 1. Mean \pm s for participants in study 1 and study 2 at each load for all variables. Data for 30%BM represents 20 participants for study 1 (10 EXP and 10 NON). * and bold indicates significant difference ($P < 0.05$) between loading conditions whilst 'b' indicates a trend for difference ($0.05 < P < 0.10$) between loading conditions.

		10% BM		15% BM		20% BM		25% BM		30% BM	
		Head	Back	Head	Back	Head	Back	Head	Back	Head	Back
$\dot{V}O_2$ (ml.kg ⁻¹ .min ⁻¹)	All	9.8 ± 2.6*	8.0 ± 2.2*	9.8 ± 2.4 ^b	8.6 ± 2.1 ^b	10.3 ± 2.4	9.2 ± 2.3	10.5 ± 3.0 ^b	9.3 ± 2.3 ^b	11.5 ± 3.3*	9.6 ± 2.9*
	EXP	8.8 ± 1.8 ^c	7.7 ± 2.7 ^c	9.2 ± 1.4 ^c	7.9 ± 2.4 ^c	9.5 ± 19 ^c	8.8 ± 2.6 ^c	9.6 ± 2.4	9.1 ± 2.6	10.8 ± 2.7	9.2 ± 3.6
	NON	11.0 ± 1.8 ^c	8.4 ± 2.9 ^c	10.6 ± 1.4 ^c	9.3 ± 2.5 ^c	11.2 ± 1.9 ^c	9.7 ± 2.7 ^c	11.6 ± 2.4	9.6 ± 2.7	12.0 ± 2.8	9.9 ± 3.8
	TA	13.1 ± 1.3	12.5 ± 1.1			15.3 ± 1.7	14.3 ± 1.6			17.3 ± 2.4	16.2 ± 1.3
$\dot{V}e$ (lmin ⁻¹)	All	21.0 ± 5.6*	17.9 ± 4.8*	21.4 ± 5.3*	19.3 ± 5.1*	22.2 ± 5.8*	20.3 ± 5.0*	23.1 ± 6.5 ^b	21.4 ± 5.6 ^b	23.5 ± 6.7*	20.8 ± 5.3*
	EXP	18.2 ± 4.1	17.3 ± 6.0	19.3 ± 4.0	18.5 ± 5.9	19.7 ± 5.5	19.9 ± 5.4	20.6 ± 6.3	20.6 ± 6.2	21.0 ± 5.8	20.2 ± 6.6
	NON	24.4 ± 5.0*	18.7 ± 6.4*	23.7 ± 4.1 ^b	20.2 ± 6.2 ^b	25.2 ± 5.2*	20.7 ± 5.7*	26.0 ± 6.5 ^b	22.4 ± 6.4 ^b	25.9 ± 5.9	21.5 ± 6.7
	TA	23.1 ± 4.4	22.3 ± 4.6			26.7 ± 4.8*	22.5 ± 4.1*			29.6 ± 8.1	25.7 ± 4.6
$\dot{V}co_2$ (ml.min ⁻¹)	All	538 ± 182*	457 ± 146*	541 ± 179*	490 ± 156*	566 ± 187	530 ± 171	593 ± 203 ^b	539 ± 182 ^b	610 ± 218*	523 ± 167*
	EXP	450 ± 149 ^d	432 ± 192 ^a	473 ± 132 ^c	458 ± 184 ^c	484 ± 164	512 ± 194	515 ± 191	523 ± 215	536 ± 200	501 ± 208
	NON	643 ± 150 ^d	487 ± 202 ^a	621 ± 138 ^c	529 ± 194 ^c	664 ± 171	550 ± 204	685 ± 200	558 ± 226	684 ± 211	546 ± 220
	TA	734 ± 84	665 ± 123			855 ± 96*	681 ± 80*			963 ± 226*	799 ± 73*
TV (ml)	All	763 ± 217*	678 ± 177*	743 ± 182	688 ± 176	759 ± 189	710 ± 186	764 ± 220 ^b	705 v 206 ^b	765 ± 211 ^b	690 ± 213 ^b
	EXP	661 ± 216 ^a	639 ± 228 ^a	671 ± 168 ^a	644 ± 214 ^a	674 ± 197 ^a	660 ± 226 ^a	671 ± 237 ^a	652 ± 252 ^a	676 ± 208	652 ± 261
	NON	884 ± 218 ^{a,c}	724 ± 234 ^{a,c}	827 ± 160 ^a	739 ± 217 ^a	858 ± 198 ^a	769 ± 223 ^a	874 ± 230 ^a	767 ± 247 ^a	854 ± 217	728 ± 267
	TA	971 ± 228	882 ± 131			1011 ± 146	841 ± 81			1054 ± 248	918 ± 56
BF (breaths.min ⁻¹)	All	28.2 ± 6.1*	26.7 ± 4.7*	29.2 ± 5.4	28.3 ± 4.9	29.8 ± 6.5	29.2 ± 5.7	31.0 ± 7.0	31.5 ± 7.6	31.2 ± 6.3	31.3 ± 7.5
	EXP	27.8 ± 7.9	27.2 ± 6.0	28.9 ± 6.9	28.9 ± 5.7	29.3 ± 8.6	30.3 ± 7.0	30.8 ± 9.1	32.0 ± 9.9	31.0 ± 7.8	31.8 ± 9.7
	NON	28.7 ± 6.4	26.2 ± 5.6	29.6 ± 5.8	27.6 ± 5.5	30.5 ± 6.8*	27.8 ± 5.3*	31.1 ± 7.3	30.8 ± 6.8	31.5 ± 6.8	30.8 ± 7.1
	TA	25.9 ± 7.1	26.6 ± 3.3			27.8 ± 5.1	27.9 ± 4.3			29.4 ± 7.5	29.0 ± 5.7
HR (beats.min ⁻¹)	All	108 ± 12*	101 ± 11*	111 ± 12*	104 ± 11*	112 ± 13*	106 v 12*	115 ± 14*	110 ± 13*	119 ± 13*	111 ± 13*
	EXP	107 ± 11	101 ± 13	109 ± 12	105 ± 14	109 ± 14	106 ± 15	112 ± 15	110 ± 15	118 ± 13	112 ± 15
	NON	111 ± 12	101 ± 13	113 ± 13 ^b	103 ± 14 ^b	116 ± 15*	107 ± 15*	119 ± 16	110 ± 16	120 ± 13	111 ± 15
	TA	114 ± 17*	96 ± 15*			120 ± 18*	104 ± 16*			127 ± 25*	114 ± 16*
RER	All	0.88 ± 0.11	0.87 ± 0.07	0.88 ± 0.12	0.87 ± 0.08	0.88 ± 0.09	0.87 ± 0.08	0.88 ± 0.10	0.88 ± 0.07	0.86 ± 0.06	0.86 ± 0.08
	EXP	0.87 ± 0.09	0.87 ± 0.09	0.87 ± 0.08	0.89 ± 0.09	0.87 ± 0.08	0.89 ± 0.09	0.87 ± 0.09	0.89 ± 0.09	0.84 ± 0.06	0.88 ± 0.10
	NON	0.89 ± 0.10	0.86 ± 0.09	0.89 ± 0.08	0.85 ± 0.10	0.90 ± 0.07 ^b	0.85 ± 0.09 ^b	0.90 ± 0.10	0.87 ± 0.09	0.89 ± 0.06	0.84 ± 0.10
	TA	0.83 ± 0.04	0.83 ± 0.08			0.84 ± 0.04	0.84 ± 0.07			0.84 ± 0.06	0.85 ± 0.05

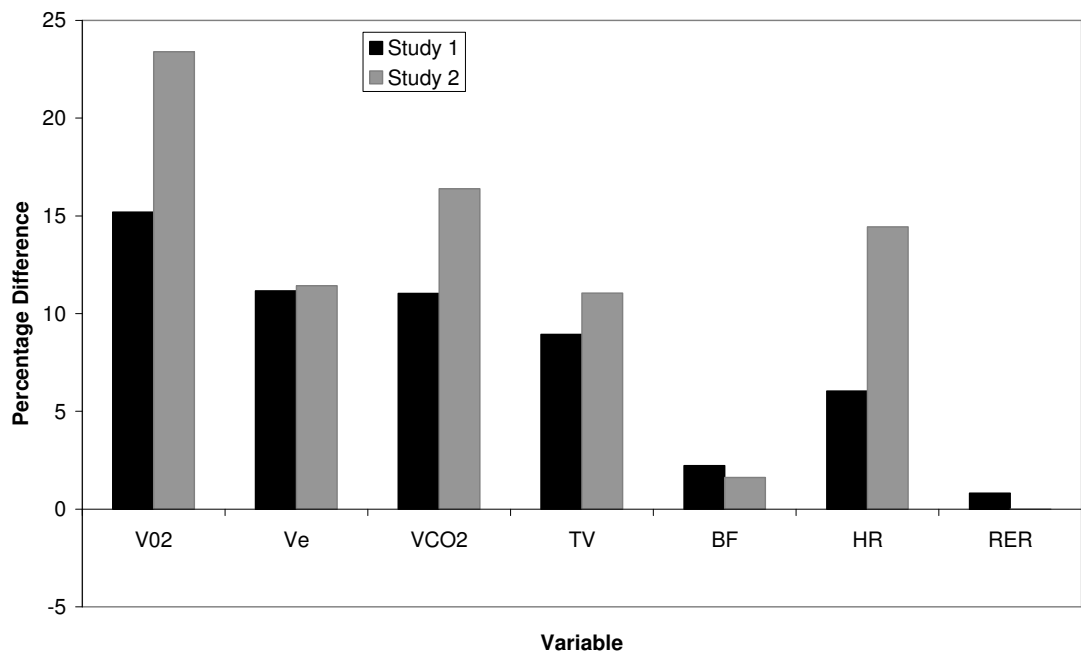


Fig 4 Overall percentage difference, calculated as increase above back-load condition, between back-loading and head-loading in cardiorespiratory variables across 10-25% BM loads (Study 1) and 10-30% BM loads (study 2)

4. Discussion

The chosen walking speed in study 1, $3.08 \pm 0.39 \text{ km} \cdot \text{h}^{-1}$, was similar to the speed employed in previous studies, in particular it is very close to the $\approx 3.0 \text{ km} \cdot \text{h}^{-1}$ defined as an optimal speed by Maloiy *et al* (1986). The speed chosen in study 2, $4.33 \pm 0.19 \text{ km} \cdot \text{h}^{-1}$, was significantly greater than that chosen in study 1 and presumably reflected the participants habituation to military marching speeds. As a consequence of this difference in locomotion speed, as well as factors such as fitness and load carriage history, no direct quantitative comparisons will be made

in respect of cardiorespiratory parameters. Any comparisons between the two studies will be restricted to similarity or difference in pattern of response.

The data for oxygen consumption associated with the back-loading condition in study 1 were, at least for the higher loads, consistent with previous studies, displaying a proportional increase in oxygen consumption with increasing load as reported by Taylor *et al* (1980). Mean percentage increases over the unloaded condition were 19.9% and 23.3% at loads of 20% and 25% BM respectively. At the lower loads, 10% and 15% BM, the mean percentage changes were 3.4% and 11.3%. These were lower than might have been predicted but they were consistent with the data of Abe *et al* (2004) who reported a less than expected increase in energy expenditure for back-loading when relatively light loads were carried at slow speeds. In particular, they reported that loads of 6 kg, 9 kg and 12 kg carried at speeds of 3.0 and 3.6 km·h⁻¹ were associated with significantly reduced energy cost of walking per unit distance when compared to unloaded walking. These speeds and load combinations are similar to those employed in study 1 where the average walking speed was 3.05 km·h⁻¹ and the average loads at 10% and 15% BM were 6.6 kg and 9.9 kg respectively. Abe *et al* (2004) argued that this phenomenon was a consequence of the interaction between increased ‘rotative torque’, presumably associated with the forward lean that accompanies back-loading (Lloyd and Cooke 2000b), and load on the lower limbs. The absence of this phenomenon for head-loading at first seems to provide some support for this idea. However, in the present study, the changes in oxygen consumption for the 10% and 15% BM loads associated with head-loading were 19.6% and 20.3% respectively. Given that forward lean is not present during head-loading, it would be reasonable to assume that the increased ‘rotative torque’ is absent. The data from study 2, where the reduction in energy cost was absent

(mean percentage changes of 8.9%, 21.0% and 37.5% for loads of 10%, 20% and 30% BM respectively), provides further support for the data of Abe *et al* (2004) as the walking speed for these participants was much greater ($4.3 \pm 0.2 \text{ km h}^{-1}$). More research is required to tease out the precise mechanisms for the energy saving phenomenon that seems to exist in certain conditions and, in particular, why it is both speed and load dependent.

In terms of other variables reported in the results which are either directly or indirectly related to oxygen consumption, such as minute ventilation, tidal volume, breathing frequency and heart rate, they are consistent with the patterns of response shown for oxygen consumption across the two studies. As expected, when oxygen consumption is greater then so is the minute ventilation and heart rate. The tendency for tidal volume to be greater during head loading could possibly be explained by postural differences and any possible chest restriction associated with wearing a backpack, especially since the tendency for a greater tidal volume was consistent with increasing loads. This is consistent with previous studies that have reported impaired abilities to increase tidal volume with increasing backpack load as a consequence of compromise to the respiratory muscles (Li *et al*, 2003; Lloyd and Cooke, 2000b). The increase in breathing frequency with loading is to be expected, given the increased energy demands and consistency of tidal volume for each loading condition, as it explains the associated increase in minute ventilation. Overall, the results for other cardiorespiratory variables support the pattern of response shown for oxygen consumption. This provides confidence in the interpretation of differences and similarities between the loading conditions and subject groups in terms of energy expenditure.

Overall the data for oxygen consumption provide little support for the ‘free ride hypothesis’, with the head-loading being associated with significantly greater oxygen consumption than back-loading across the 10%-25% BM loads in study 1 and with a tendency for the same across the 10%-30% loads in study 2. Figure 4 clearly shows that, on average, the percentage increase in oxygen consumption for the head-loading condition consistently lies above the line $y=x$ for both study 1 and study 2. If a ‘free ride’ for head-loading exists as a generalisable phenomena then the percentage increases for head-loading should lie below this line and indeed, should move further below the line with loads between 10 and 20%. This was not the case for either of the groups studied. Considering study 1, it was anticipated that the EXP group would exhibit greater economy than the NON group when head-loading. The tendency for difference between the groups ($P=0.069$) and the lack of interaction between group and loading method ($P=0.333$) would suggest that, whilst the EXP group were generally more efficient load carriers than the NON group they were also more efficient whilst back-loading than head-loading. Again this was a somewhat unexpected finding and stands in contrast to the seminal works in this area (Maloiy *et al*, 1986; Charteris *et al*, 1989a, Charteris *et al*, 1989b). One possible explanation for this is that the participants in these early studies were considerably more experienced head-loaders than those used here. It is certainly the case that the six participants in the studies by Charteris *et al* (1989a, 1989b) were older and more experienced, age 33.7 ± 9.4 years and head-loading experience 22.5 ± 8.9 years, than the participants in the EXP group in the present study, who had at least ten years head-loading experience and were aged 22.5 ± 2.1 . Maloiy *et al* (1986) provide no data in relation to age or experience, although the participants were

characterised as experienced head-loaders. It would appear from these data that, although the participants in the present study had not been head-loaders for as long as those in the Charteris (1989a, b) studies, they had begun head-loading at approximately ten years of age, the same age as those in previous studies. It therefore seems unlikely that the differences in responses reported here can be explained by length of habituation. A more likely explanation lies in the variability of the data reported in the present study and the sample sizes of the earlier studies.

Examination of individual results in study 1 indicates that it would be possible to select a subset of women who did achieve remarkable levels of economy, in line with the previously reported data. Given the small sample sizes in most of the previous studies on head-loading this is not altogether unexpected but suggests that the 'free ride' hypothesis is not a generalisable finding, when tested with larger more representative samples of African women. Considering the oxygen consumption data across the 10-20% BM loads, five women demonstrated the 'free ride' phenomenon for head-loading (odds of selection 1:42504), with average increases above the unloaded condition of less than $0.5 \text{ ml} \cdot \text{kg}^{-1}$, whilst seven demonstrated the same phenomenon for back-loading. Only two of the women feature in both subsets, one from each group. Remarkably, four of the five most economical head-loaders were women with no experience of head-load carriage. This would seem to indicate that structural changes to the spine associated with early and prolonged exposure to head loading are unlikely to provide explanations for such efficiency in individuals as previously speculated (Maloiy *et al* 1986). Conversely, six of the seven most economical back-loaders were from the EXP group. This was somewhat less unexpected as all of the

women in the EXP group had experience of back-loading, as it is the traditional method for carrying young children, and were generally more experienced load carriers, regardless of method, than their counterparts in the NON group.

It has also been argued that body composition influences load carriage economy (Lyons *et al.* 2005) and that the explanation for the remarkable economy observed in some head-load carriers is a consequence of their low body fat (Jones *et al.* 1987), with the extent of the ‘free ride’ being determined by the combination of fat and external load up to 140% of Fat Free Mass (FFM). Whilst this is helpful in untangling some of the issues relating to the ‘free ride’ hypothesis it does not provide support for the hypothesis as has been suggested. It would only provide an explanation if all extremely economical load carriers are relatively lean – in the present study the mean \pm sd BMI for the eleven women exhibiting some form of free ride for either carrying method was $24.0 \pm 5.1 \text{ kg}\cdot\text{m}^{-2}$, implying that these women were, in general, not particularly lean. It might also be expected that if the size of the load relative to FFM is the determinant of economy then there would be a strong relationship between economy across different load carriage methods. However, in the present study it was apparent that economy in one method of carrying a load was not an indicator of economy in the other method ($r=0.128$, $P = 0.552$). This lack of association between economy and load carriage method is an important finding. It suggests that cause and effect relationships between economy and load carriage are not likely to be explained by a common set of factors for different forms of load carriage in the same individuals, whether or not they are experienced in either or both forms of load carriage under investigation. This suggests that future research, and evaluations of previously completed studies in load carriage, should focus on the mechanisms responsible for the economy of individuals rather than expecting one or more mechanism to explain

the observed variation within a particular method. This shift in focus, with a view to understanding how particular individuals carry loads more economically than others and why particular methods are more economical for some individuals than others, may provide a better understanding of the interactive effects of factors related to different forms of load carriage. There have been a number of explanations proposed for the greater economy of head-load carriage. Heglund *et al.* (1995) and Cavagna *et al.* (2002) have argued, based on an analysis of the five participants in the original Maloiy *et al.* (1986) study, that it is a consequence of improved energy exchange between gravitational potential energy and kinetic energy. Minetti *et al.* (2006), based on five experienced head-loaders carrying loads uphill but with no direct measurement of unloaded walking, suggested that balancing the loaded segment above the hip was an important mechanism. Abe *et al.* (2004) and Abe *et al.* (2008) reported an energy saving phenomenon at some load-speed interactions for back-loading and argued that this was a consequence of the interaction between 'rotative torque' and the burden on the lower limbs. In light of the data presented here it may be that such mechanisms are best examined on a case by case basis, attempting to account for individual difference rather than seeking general explanations. This may have implications for both military and recreational applications as it is likely to be the case that either the optimum load carriage system may be specific to an individual or that particular carrying methods require different techniques. Clearly individualisation of load carriage strategies may be impossible for most applications, although in some particularly sensitive cases it may be worthwhile. Nevertheless, an understanding of the factors that lead to improved economy in particular individuals, rather than pooled results, may well provide a useful way forward in the design and customisation of load carriage systems.

5. Conclusion

The data presented here suggest that the ‘free ride hypothesis’ for head-loading is not a generalisable finding. The proportional increases in energy consumption are generally greater than the proportional increases in external load for both African and British women, regardless of head-loading experience. There was, however, some evidence of an energy saving effect when light loads were carried on the back at low speeds, further work is required to establish the mechanisms responsible for such a phenomenon. The data also revealed significant variation in load carrying economy, regardless of method, suggesting that there may not be a single set of factors determining load carriage economy but rather that different factors may align in individuals to influence economy. Further work is required to establish the nature of these factors and how they interact in individuals. Such information may well be useful when minimizing the energetic cost of load carriage is particularly important.

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